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¹ Sound absorption by clamped poroelastic plates

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Measurements and predictions have been made of the absorption coefficient and the surface acoustic impedance of poroelastic plates clamped in a large impedance tube and separated from the rigid termination by an air gap. The measured and predicted absorption coefficient and surface impedance spectra exhibit low frequency peaks. The peak frequencies observed in the absorption coefficient are close to those predicted and measured in the deflection spectra of the clamped poroelastic plates. The influences of the rigidity of the clamping conditions and the width of the air gap have been investigated. Both influences are found to be important. Increasing the rigidity of clamping reduces the low frequency absorption peaks compared with those measured for simply supported plates or plates in an intermediate clamping condition. Results for a closed cell foam plate and for two open cell foam plates made from recycled materials are presented. For identical clamping conditions and width of air gap, the results for the different materials differ as a consequence mainly of their different elasticity, thickness, and cell structure.

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20 I. INTRODUCTION

Sound absorbers including porous materials are used widely for noise control. The most widely exploited and acknowledged absorption mechanism in porous materials is viscous friction due to relative motion between solid and fluid. If the frame of the porous material is viscoelastic then other dissipative mechanisms are possible. To obtain good low frequency absorption, say, below 300 Hz, exploiting the viscous friction mechanism alone may require an unacceptably large thickness of material. In designing passive sound absorbers based on porous materials or membranes, it is known that the presence of a backing air gap with properly chosen dimensions can enhance their low frequency performance. If a porous plate is elastic then a backing air cavity will allow bending modes which could lead to significant absorption at relatively low frequencies. Indeed such low frequency absorption maxima have been observed for configurations consisting of clamped poroelastic plates with an air gap behind them¹. It has been found that the coupling between airborne sound and bending vibrations in the plates is increased if the flow resistivity is high. Depending on its thickness, the presence of an air gap has been thought previously to favor or hinder structural vibration but not to change the resonance frequencies which are considered to be solely dependent on the plate's mechanical properties, the clamping conditions, and the microstructural parameters (porosity, tortuosity, and flow resistivity)¹.

Takahashi and Tanaka² developed an analytical model by introducing flow continuity at the plate surface in a spatially mean sense and air-solid interaction within the plate material. However, their formulation does not allow for clamping at the boundaries of the plates. Horoshenkov *et*

al.^{3,4} formulated a model for the acoustic response of elastic porous plates and the effect of plate vibration. They have used a coupling condition between the plate and surrounding air at the plate surface and have shown that the low frequency resonant peaks observed in the surface impedance of the clamped plates with air backing are related to modes of vibration of the plates. Leclaire *et al.*⁵ presented a variational method for solving the plate equations for different porous elastic plates with the four edges clamped but have neglected the effect of fluid loading on the plate vibration and have not taken into account external forces other than the excitation terms. Recently Aygun *et al.*^{6,7} included the effects of fluid loading on the vibration of clamped, rectangular porous elastic plates by solving the governing equations for flexural vibration. Attenborough and Aygun⁸ demonstrated the existence of low frequency absorption coefficient resonances in configurations consisting of clamped poroelastic plates with an air gap between the plates and a rigid termination. As well as the size of the plate and the corresponding clamping conditions, the width of the rear air gap is found to alter the absorption peak magnitudes and frequencies. This paper reports these results in greater detail together with additional data and predictions.

Measurements have been made of the absorption coefficient and the acoustic surface impedance of a closed cell [polyvinylidene fluoride (PVDF)] foam plate and two open cell foam plates made from recycled materials clamped in a large impedance tube with concrete walls. The tube has been designed to enable measurements between 50 and 300 Hz. The measured absorption coefficients have been compared with those predicted for fluid loaded, clamped, rectangular porous elastic plates. To investigate the importance of porosity, comparative predictions have been made for nonporous plates with the same elasticity parameters as the poroelastic plates. To emphasize the importance of the elasticity of the clamped porous plate, calculations have been made also of

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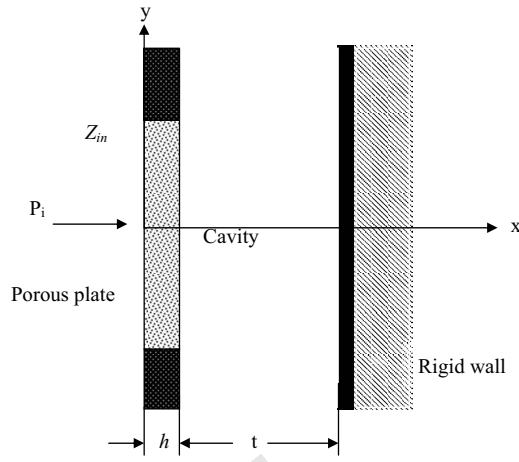


FIG. 1. Schematic of a poroelastic plate in a rigid baffle separated from a rigid wall by an air gap.

TABLE I. Measured and deduced (*) properties of the poroelastic plates.

	YB10 foam plate	PVDF foam plate	Black foam plate
L_x (m) in x direction	0.5	0.5	0.6
L_y (m) in y direction	0.5	0.5	0.6
Thickness (m)	0.0107	0.025	0.021
Density ρ (kg/m ³)	353	25.15	223
Young's modulus (Pa)	2.1×10^7	254 600*	2.46×10^6
Loss factor	0.1	0.15*	0.35
Poisson ratio ν	0.35	0.35*	0.3
Porosity ϕ	0.69	0.2	0.75
Tortuosity τ_∞	1.2	1*	1.85
Permeability κ (m ²)	2.7×10^{-10}	3.24×10^{-11}	3.92×10^{-10}
Flow resistivity N s m ⁻⁴	68 111	567 901	46 933

Eq. (2) assumes that the plate is of infinite length, the calculations of w_p assume some form of clamping at all four edges and have been made using

$$w_p(z) = \sum_{m=1}^{\infty} W_m^p Z_m(z), \quad (3)$$

where $Z_m(z)$ are the beam functions and W_m^p is the plate lateral displacement. Expressions for W_m^p are given elsewhere.^{6,7}

The normal incidence sound absorption coefficient is given by

$$\alpha(\omega) = 1 - \left| \frac{\langle Z \rangle - 1}{\langle Z \rangle + 1} \right|^2. \quad (4)$$

III. MEASUREMENTS

Measurements have been carried out in a large 6 m long rectangular impedance tube with an internal cross section of 50×50 cm² and external cross section of 65×65 cm² (see Fig. 2). The center-to-center spacing between two microphones is 20 cm. The distance from the test sample to the center of the nearest microphone is 50 cm. A standard procedure¹⁰ has been followed during the measurements.

The acoustic sound field was created by a loudspeaker fed by a noise generator and a 600 W power amplifier. Two $\frac{1}{2}$ in. B&K microphones were mounted into microphone grid at positions along the length of the impedance tube. Each microphone grid was sealed tight to its housing. The microphones were supported by two preamplifiers which were

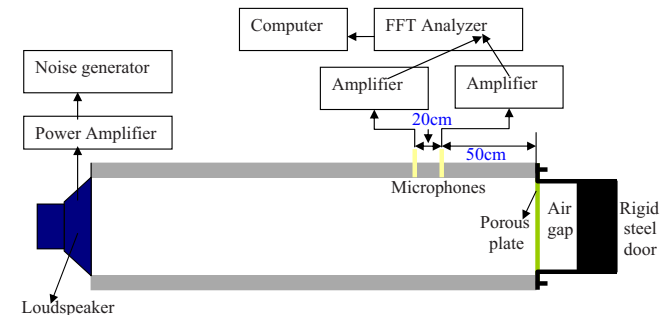


FIG. 2. (Color online) Impedance tube arrangement (Ref. 7).

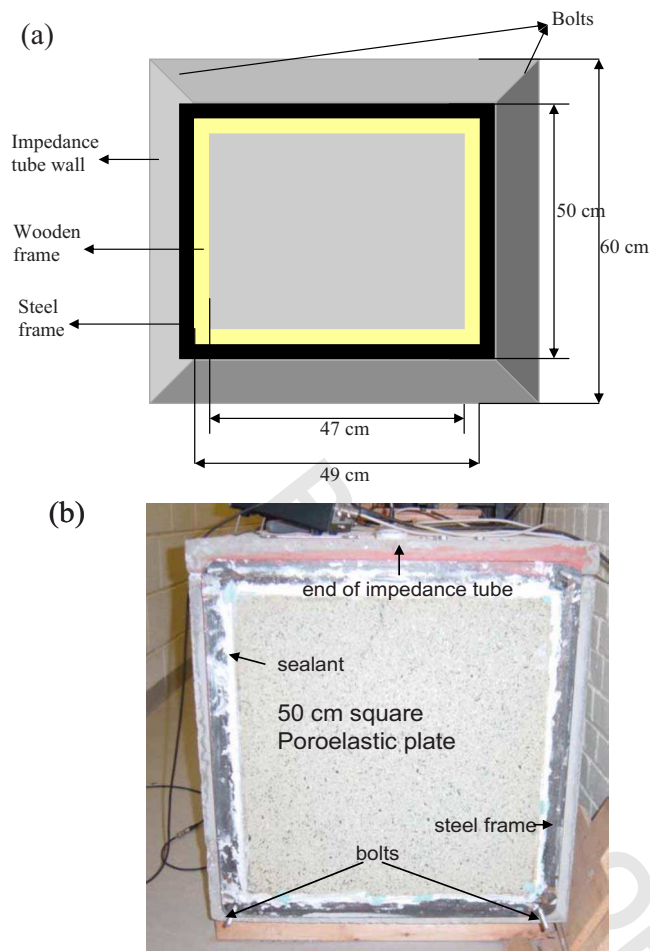


FIG. 3. (Color online) (a) A diagram of the end of the impedance tube and the plate clamping arrangement. (b) Photograph showing a 50 cm square YB10 plate mounted at the end of the impedance tube.

ance tube and the rigid backing using the bolts, the smaller plate size means that the clamping was not as tight as was the case for the “rigidly clamped” conditions.

As well as different sizes of two types of plate, three different types of plate materials have been used in the impedance tube measurements. The PVDF foam was 25 mm thick and predominantly closed cell. YB10 and Black plates, 10.7 and 21 mm thick, respectively, were open cell foams fabricated from recycled car dashboards. The measured and deduced properties of the poroelastic plates are given in Table I.

The listed properties of the recycled foam plates (Black and YB10) were measured at the University of Bradford. The permeability of the PVDF foam has been calculated from the measured flow resistivity ($567\,700\text{ N s m}^{-4}$). The elastic modulus of the PVDF Foam has been deduced from vibration data. Values of the loss factor, Poisson’s ratio, and tortuosity values for the PVDF foam have been deduced by fitting the surface impedance data. The deduced properties are distinguished by asterisks in Table I.

IV. RESULTS OF MEASUREMENTS

The surface acoustic impedance $\langle Z \rangle$ at the front surface of the poroelastic plate is calculated from measurements by using

$$\langle Z \rangle = (1 + R_c)/(1 - R_c). \quad (5)$$

R_c , the complex reflection coefficient, is given by¹⁰

$$R_c = \frac{H - e^{iks}}{e^{-iks} - H} e^{j2k(l+s)}, \quad (6)$$

where l is the distance from the test sample to the center of the nearest microphone, s is the center-to-center spacing between microphones, and H is the measured transfer function of the two microphone signals corrected for microphone response mismatch.

The corresponding normal incidence absorption coefficient is obtained from

$$\alpha = 1 - |R_c|^2. \quad (7)$$

A. Effects of changing clamping conditions and air gap width

The measured impedance and absorption coefficient spectra obtained with 50 and 60 cm square YB10 plates and a backing air gap width of 60 cm are shown in Figs. 4 and 5, respectively. The absorption coefficient spectra show useful low frequency peaks. The different sizes of plates result in different edge clamping conditions. As remarked earlier, it was not possible to obtain as rigidly clamped conditions with the smaller YB10 plate ($50 \times 50\text{ cm}^2$) as was possible when using the larger plates. According to these data, the magnitudes and frequencies of the surface acoustic impedance and corresponding absorption coefficient peaks are significantly affected by the rigidity of the clamping conditions. The less rigid, intermediate clamping results in higher absorption peaks.

connected to two B&K measuring amplifiers. The outputs of the measuring amplifiers were fed to a two-channel fast Fourier transform analyzer which was connected to a computer for data analysis. The porous plate was separated from rigid steel door at the end of the tube by an air gap to allow bending vibration (see Fig. 2). The edges of the porous elastic plates being tested were clamped in a steel frame fitted inside the impedance tube. The edges of the porous elastic plate were compressed between the end of the impedance tube and the rigid backing system by using four bolts. The edges of 60 cm square plates were further secured in an additional wooden frame (see Fig. 3) which reduced the exposed area of the plates to $47 \times 47\text{ cm}^2$, i.e., the distance between the clamped edges of the porous elastic plate was 47 cm. Subsequently this condition is called “rigid” clamping (CCCC).

To achieve “simply supported” boundary conditions (denoted by SSSS in the figures), the smaller (50 cm square) plates were glued to the edges of the steel frame rather than clamped. Any gaps between the plate and frame were sealed by using double sided tape and sealant. A third type of clamping condition, subsequently described as “intermediate,” was obtained with the 50 cm square plates by gluing them to the edges of the steel frame. Although the edges of the plates were compressed between the end of the imped-

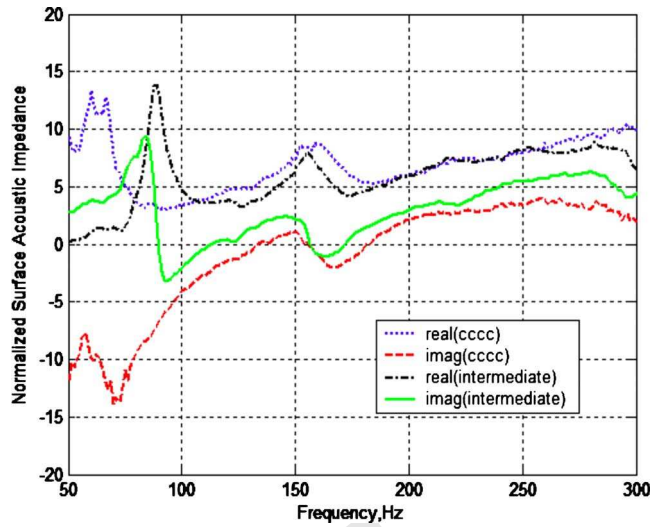


FIG. 4. (Color online) A comparison of the measured normalized surface acoustic impedance spectra for 60 and 50 cm square YB10 plates in front of a 60 mm wide air gap. The corresponding clamping conditions are rigidly clamped (CCCC) and “intermediate,” respectively.

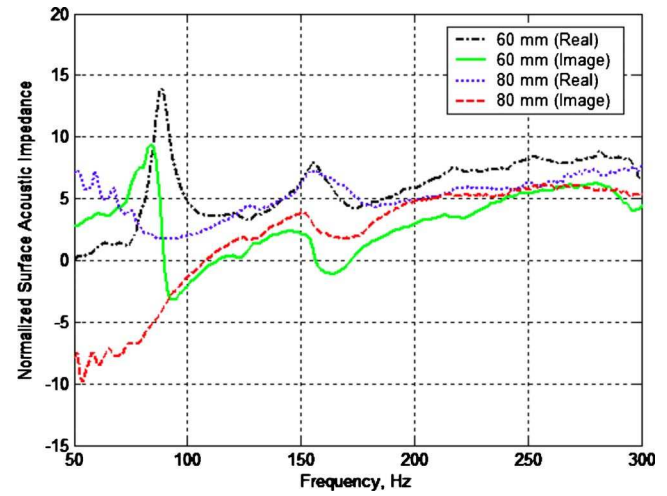


FIG. 6. (Color online) A comparison of measured normalized surface acoustic impedance spectra for the YB10 plate with 60 and 80 mm air gaps and intermediate clamping conditions.

this resonance to increase in magnitude. The differences between curves in Fig. 8 are because of the depth of the air gap and different boundary conditions.

B. Comparative performance of different plate materials

Even with simply supported boundary conditions, the low frequency absorption peaks obtained with the Black plate are significantly less pronounced than those obtained with YB10 plate. The YB10 plate is much stiffer than the Black plate. Moreover the thickness of the Black plate is almost double that of the YB10 plate.

The measured real and imaginary parts of the surface acoustic impedance of $50 \times 50 \text{ cm}^2$ PVDF foam and YB10 foam plates, subject to intermediate clamping conditions, are shown in Fig. 9. The corresponding absorption coefficient spectra are compared in Fig. 10.

The measured surface impedance spectra for the YB10 foam plate exhibit a more pronounced resonant structure

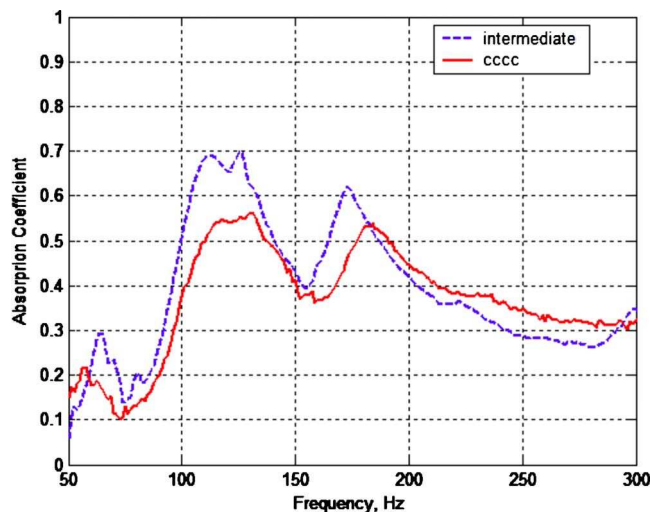


FIG. 5. (Color online) Measured absorption coefficient spectra corresponding to Fig. 4 (Ref. 7).

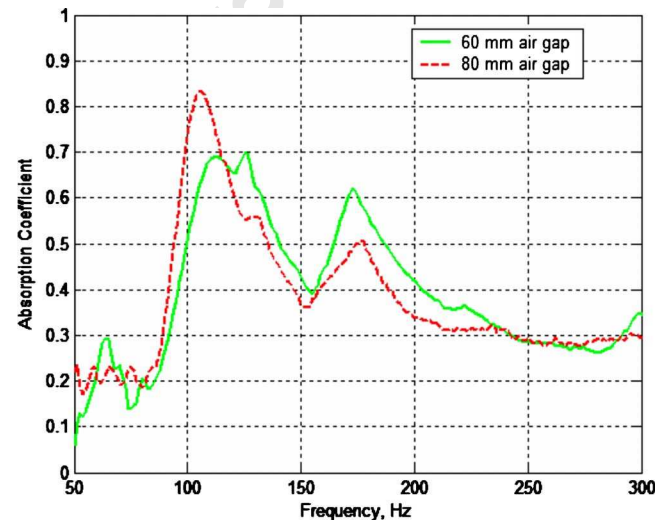


FIG. 7. (Color online) Measured absorption coefficient spectra corresponding to Fig. 6 (Ref. 7).

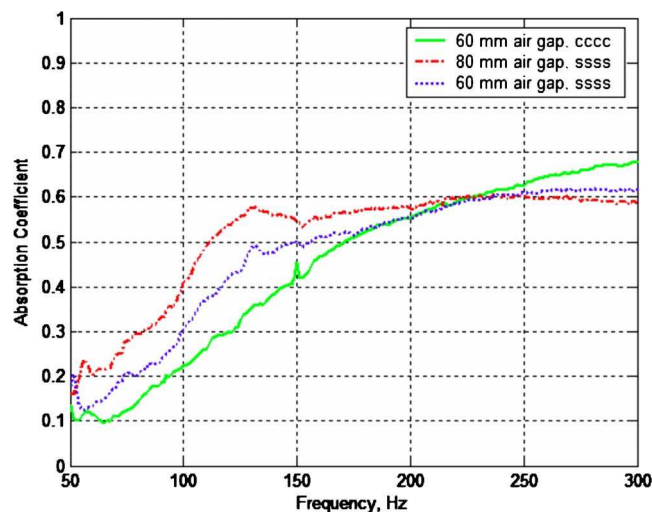


FIG. 8. (Color online) Measured absorption coefficient spectra obtained with a 60 cm square Black plate with 60 and 80 mm wide air gaps and rigid (CCCC) and simply supported (SSSS) edge conditions.

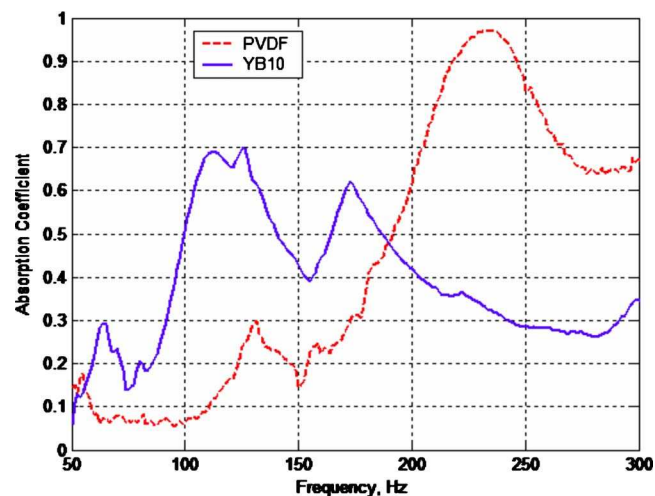


FIG. 10. (Color online) Measured absorption coefficient spectra corresponding to Fig. 9 (Ref. 7).

than those for the PVDF foam plate. The PVDF plate yields a lower absorption coefficient than the YB10 plate below 190 Hz. However, the major resonance in the absorption coefficient of the PVDF plate at 232.5 Hz means that it has a higher absorption coefficient than the YB10 foam plate above 190 Hz. There are minima in the PVDF plate absorption spectrum at 150 and 280 Hz compared with 70 and 155 Hz for the YB10 plate.

V. COMPARISONS BETWEEN PREDICTIONS AND DATA

Figure 11 compares the measured absorption coefficient spectra of the rigidly clamped YB10 plate with those predicted for fluid loaded, rigidly clamped, rectangular porous elastic plate using the properties listed for the YB10 plate in Table I. Also shown are predictions for a hypothetical nonporous plate having the same elastic properties as the porous

elastic plate used in the measurements. Although the agreement between predictions and measurements is not particularly good, the predictions that include the effects of porosity are clearly superior. They match the frequency and magnitude of the peak between 100 and 150 Hz fairly well and the relative magnitudes of the other two peaks. The predicted absorption coefficient for a hypothetical nonporous plate is below 0.15 throughout the frequency range. This suggests that the presence of porosity increases the absorption of the poroelastic plate configuration. The depth of the air gap used when obtaining the data shown in Figs. 11 and 12 was 60 cm.

Figure 12 compares the measured absorption coefficient spectra of the PVDF plate, under intermediate clamping, with those predicted for fluid loaded, rigidly clamped, rectangular porous and nonporous elastic plates having the properties listed for PVDF plate in Table I. Again the predictions including porosity are superior in that the frequency and

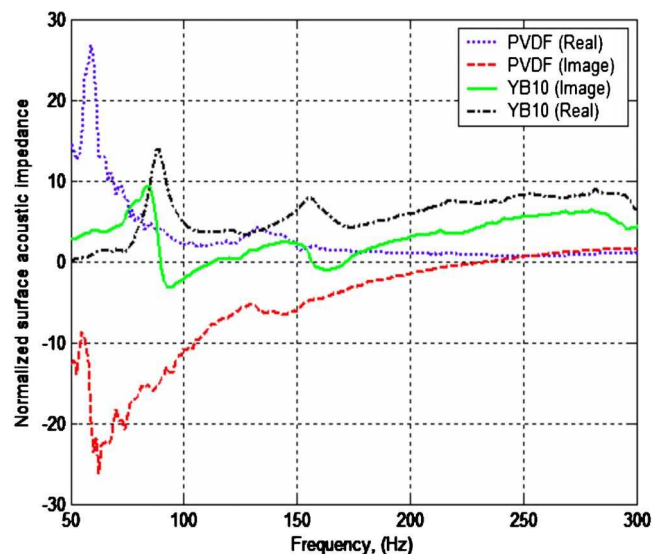


FIG. 9. (Color online) A comparison of measured normalized surface acoustic impedances of the PVDF and YB10 foam plates with 60 mm wide air gap behind the plates and intermediate clamping conditions.

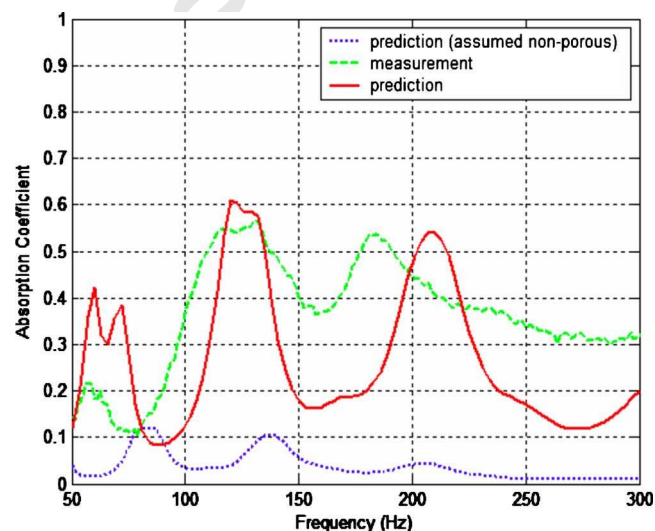


FIG. 11. (Color online) A comparison of the measured and predicted absorption coefficient spectra for a rigidly clamped YB10 plate. Predictions are shown for both porous and nonporous plates.

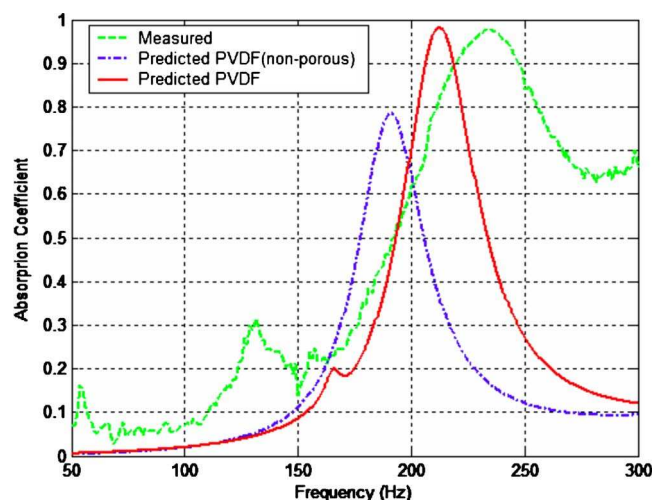


FIG. 12. (Color online) A comparison of the measured absorption coefficient of the PVDF plate, under intermediate clamping conditions, to the predicted absorption coefficients of rigidly clamped porous and nonporous PVDF plates.

and 170 Hz) of the peaks observed in the absorption coefficient spectra for the YB10 foam plate (Fig. 7).

To further emphasize the importance of the elasticity to the acoustical performance of the clamped porous plates, calculations have been made also of the surface impedance and normal incidence absorption coefficient of a rigid-porous plate with the same pore-related properties as the porous elastic plate. Figure 14 shows predictions, using the Johnson–Allard model,⁹ of the surface impedance and absorption coefficient spectra below 300 Hz of a rigid-porous plate with and without a 60 mm wide air gap in front of a rigid termination. The plate is assumed to have the same pore-related properties as the YB10 plate (from Table I). Figure 14 shows that, even with an air gap, the absorption coefficient for the rigid-porous plate is predicted to be below 0.45 throughout the frequency range. The fact that these predictions do not contain any peaks provides further confirmation that the peaks observed in measurements (Figs. 4–12) are related to plate vibration resonances and that to obtain useful low frequency absorption peaks a clamped plate should be porous, elastic, and have a backing air gap.

The low frequency absorption peaks obtained with the Black plate are significantly less pronounced than those obtained with the YB10 plate even with the same boundary conditions. There are differences in stiffness, thickness, and porosity-related parameters. The YB10 plate is much stiffer than the Black plate. Using Eqs. (1)–(4), the predicted effect of decreasing Young’s modulus only is to increase the absorption coefficient peaks and move them to higher frequency. The thickness of the Black plate is almost double of the YB10 plate. The predicted effect of only increasing the thickness of the YB10 plate from 10.7 to 20 mm is to decrease the absorption coefficient of the YB10 plate to below 0.1 throughout the frequency range. Porosity has an important effect on predictions of the absorption coefficient only if it is varied independent of the flow resistivity. However, this is unphysical since flow resistivity will depend on porosity as well as on cell structure. Change in flow resistivity only is predicted to have a relatively small effect on the absorption coefficient. On this basis, the observed differences in absorption spectra between Black and YB10 plates can be attributed primarily to differences in thickness and stiffness.

The PVDF and YB10 plates have different Young’s modulus, thickness, porosity, density, flow resistivity, and cell structure. Specifically, the PVDF plate has higher flow resistivity and thickness but lower porosity and Young’s modulus. For a given (intermediate) clamping condition, although the predicted effect of decreasing Young’s modulus alone is to increase the absorption coefficient peaks and move them to higher frequency, the predicted effect of increasing thickness alone is to reduce the absorption peaks, as observed when comparing the YB10 plate performance with the Black plate. Moreover the predicted effect of increasing flow resistivity is not very significant. The comparative failure of theory, which assumes an open cell structure, to predict the acoustical performance of the clamped PVDF plate seems, therefore, to be related to its predominantly closed cell structure.

magnitude of the resonant peak are closer to those measured. However, the predicted influence of porosity is much less for this predominantly closed cell foam. An additional reason for differences between the predictions and data is that the theory assumes open cells, whereas the PVDF plate has predominantly closed cells.

To investigate the extent to which the surface impedance resonances are related to plate vibration, measurements have been made of the deflection spectra while the plates were clamped in the impedance tube. Figure 13 shows the deflection at the center of the YB10 plate measured using an accelerometer while it was clamped in the impedance tube and subject to broadband sound. Also shown is the deflection spectrum predicted by using Leclaire’s theory⁵ modified to include fluid loading^{6,7} and assuming a uniform oscillatory driving pressure corresponding to a plane wave at normal incidence. The observed and predicted deflection maxima at 60, 120, and 170 Hz are close to the frequencies (58.75, 130,

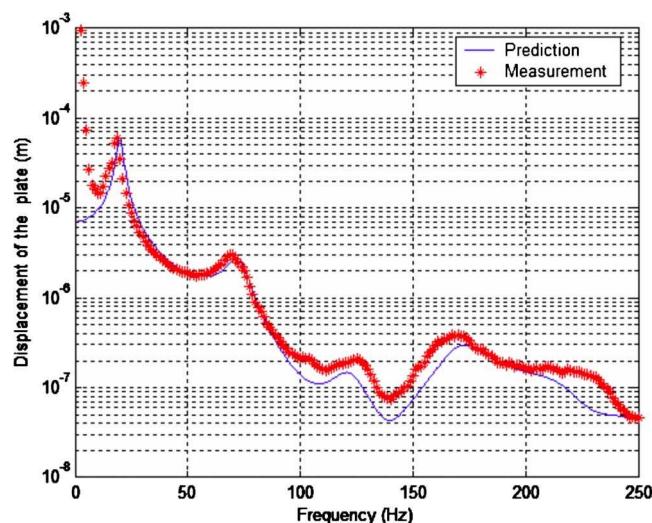


FIG. 13. (Color online) A comparison of measured and predicted deflection spectra of a rigidly clamped YB10 plate subject to uniform oscillatory pressure (Ref. 8).

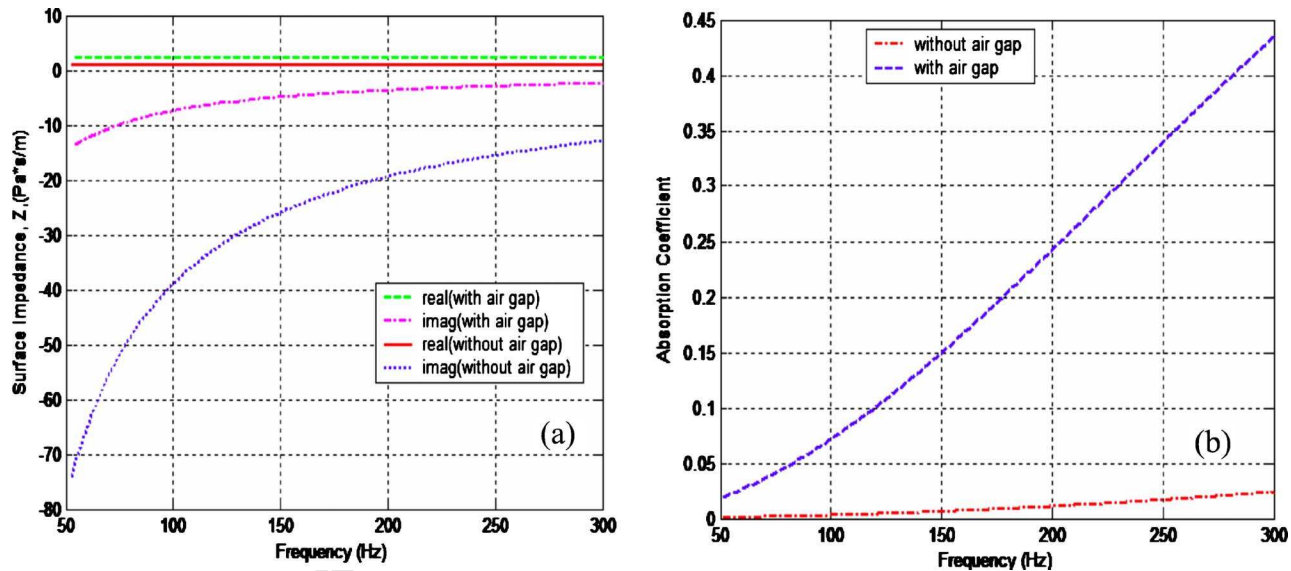


FIG. 14. (Color online) Predicted (Ref. [1]) surface impedance and (b) absorption coefficient spectra of a rigid-porous plate having the pore-related properties of the YB10 plate with and without an air gap.

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VI. CONCLUSIONS

Measurements have been made of the absorption coefficient and the surface acoustic impedance of clamped porous elastic plates with an air gap in front of the rigid termination of a large impedance tube. These show resonances below 300 Hz that may be useful for noise control and are similar to those previously reported.¹ Here they have been shown to be at frequencies close to those of the maxima measured and predicted in the plate deflection spectra. A hybrid model, formulated by incorporating the predictions of clamped fluid loaded poroelastic plate vibration in the expression for surface impedance of an equivalent fluid plate of infinite length, has been found to give tolerable agreement with data. The discrepancies between predictions and measurements may be due to several factors including assumptions made in the theory, uncertainties in plate properties, and poor practical realizations of the assumed boundary conditions. However, the relative insensitivity of the predictions to plate parameters suggests that the other two causes are likely to be the more important ones. The low frequency resonances have been shown to depend on the clamping conditions and the width of the backing air gap in addition to the pore- and elasticity-related properties and thickness of the plates. Increasing the rigidity of the clamping is found to reduce the low frequency absorption peaks. The dependence on clamping conditions may explain the fact that, although two of the materials tested (YB10 and Black) are nominally similar to those tested previously by others,¹ contrasting results have been obtained here. Three low frequency absorption peaks have been observed for the YB10 plate compared with the single relatively small low frequency absorption peak observed elsewhere.¹ Moreover, according to our data, Black plates perform less well than YB10 plates. An intermediately clamped 25 mm thick plate of closed cell foam (PVDF) has been found to give a substantial absorption coefficient peak

below 300 Hz. The markedly different absorption coefficient spectra observed with the predominantly closed cell PVDF plate compared with the YB10 plate for similar clamping conditions appear to result from the different cell structures rather than from differences in stiffness, flow resistivity, and thickness and this should be the subject of further work.

ACKNOWLEDGMENTS

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- ⁹J.-F. Allard, *Sound Propagation in Porous Media* (Elsevier Applied Science, New York, 1993), pp. 76–93 and Eqs. (5.62)–(5.66).
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